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Space systems — Structural design — Stress analysis requirements

Systemes spatiaux — Conception des structures — Demandes vers l'analyse des contraintes

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

ISO 16454 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

From the beginning of the space age, structure integrity verification was one of the main field of mechanical specialists activity. Mission failure, possible danger to human life, expensive ground constructions, other public and private property are the most probable consequence in the case of loss of space structure integrity. Static strength is one of the most important critical condition for structure integrity analysis. Usually it is the main criteria for space structure weight evaluation. If space structure would be too heavy the mission could be too expensive or impossible. If space structure would have too thin thickness mission failure risk could be too high that lead to loss of expensive hardware and other property. It is necessary to specify unique requirements to static strength analysis to provide cost effective design and light, reliable and low risk structures for space application.

There is significant history to the analysis and design of space. This International Standard establishes the preferred requirements for these techniques for static strength critical condition.

Space systems — Structural design — Stress analysis requirements

1 Scope

1.1 General

This International standard is intended to be used for the determination of the stress/strain distribution and margins of safety in launch vehicles and spacecraft primary structure design. Liquid propellant engine structures, solid propellant engine nozzles and solid propellant itself are not covered, but liquid propellant tanks, pressure vessels and solid propellant cases are in the scope of this International standard.

This International standard provides the requirements for maximum stresses and corresponding margins of safety determination when loads are once applied, and sets out the criteria for static strength failure modes such as rupture, collapse and detrimental deformation. Critical conditions associated with fatigue, creep and fracture mechanics are not covered. Notwithstanding those scope limitations the results of stresses calculations based on the requirements of this International standard can be used for other critical conditions analysis.

1.2 Application

In accordance with requirements fixed in this International standard, models, methods and procedures for stresses determination can be also used for the displacements, deformation calculations as well as for the loads definition applied to substructures and structure members of structures under consideration. When this International standard is applied, it is assumed that temperature distribution has been determined and is used as input data.

When ISO STD 14622 application is specified by a contract, load data must meet the requirements of ISO STD 14622, where only minimum values of design safety factors are established. Design safety factors used for stresses analysis and margins of safety determination may be larger and in that case their values shall be specified by a contract with accounting for national industry specifications, relevant experience, conservatism of other requirements to structure design and verification.

When ISO DIS 14623 application is specified by a contract, load data for metallic pressurized systems and overwrapped pressure vessels must meet the requirements of ISO DIS 14623.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO STD 14622:2000, *Space systems — Loads and induced environment*

ISO DIS 14623[1)], *Space systems — Pressure vessel structural design*

1) To be published

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
"A- basis allowable"
mechanical strength value above which at least 99% of the population of values is expected to fall, with a confidence level of 95%

3.2
allowable load (stress, strain)
maximum load (stress, strain) that can be accommodated by a material/structure without potential rupture, collapse, or detrimental deformation in a given environment

NOTE Allowable loads (stresses, strains) commonly correspond to the statistically based minimum ultimate strength, buckling strength, and yield strength, respectively.

3.3
basic data
input data required to perform stress analysis and to determine margins of safety

3.4
"B-basis allowable"
mechanical strength value which at least 90% of the population of values is expected to fall, with a confidence level of 95%

3.5
collapse
failure mode under compression by quasi-static loads accompanied by very rapid irreversible loss of load resistance capability

3.6
composite material
combination of materials different in composition or form on a macro scale

NOTE 1 The constituents retain their identities in the composite.

NOTE 2 Normally the constituents can be physically identified, and there is an interface between them.

3.7
creep
process of a permanent material deformation resulting from long duration under constant or slowly altered load

NOTE The ultimate creep deformation, corresponding to the loss of material integrity is often much higher than ultimate deformation in the case of short time loading.

3.8
critical condition
most severe environmental condition in terms of load and temperature, or combination thereof, imposed on a structure, system, subsystem or component during service life

3.9
critical location
structural point at which rupture, local buckling or detrimental deformation will first lead to structural failure

3.10
destabilizing load
load that produces compressive stress at critical location

3.11
detrimental yielding
permanent deformation specified at the system level to be detrimental (only for metallic structures)

3.12
development test
test to provide design information that may be used to check the validity of analytic technique and assumed design parameters, to uncover unexpected system response characteristics, to evaluate design changes, to determine interface compatibility, to prove qualification and acceptance procedures and techniques, to check manufacturing technology, or to establish accept/reject criteria

3.13
design safety factor
coefficient by which limit loads are multiplied in order to account for the statistical variations of loads and structure resistance, and inaccuracies in the knowledge of their statistical distributions

3.14
flight – type hardware test
test of flight structure article, protoflight model, representative special model or structure element fabricated with the same or close to flight hardware technology

3.15
gages
thickness and other structure dimensions which relative scattering could significantly influence on stress levels and/or margin of safety

3.16
knockdown coefficient
empirical coefficient, other than design safety factor, which is used to determine analytically in a simple way actual or allowable loads or stresses and which is defined on the basis of flight-type structures, model structures or structural members test results in comparison with corresponding stresses analysis data

3.17
limit load
maximum or minimum load (for stabilizing one) that can be expected during service life and in the presence of the environment

3.18
loads
concentrated and/or distributed over the structure surfaces or structure volume forces and moments caused by its interaction with environment and adjacent parts of vehicle, and accelerations

NOTE Pressures, external loads and enforced displacements acted at considered structure element, pretension, inertial loads caused by accelerations and thermal gradients are covered

3.19
loading case
particular condition described in terms of loads/pressures/temperatures combinations, which can occur for some parts of structure at the same time during its service life

3.20
local buckling
failure mode, which is realized when an alternative equilibrium mode of a structural member exists, and if occurred under loading could lead to detrimental deformation or rupture of that member

3.21
margin of safety (MS)
Margin of Safety (MS) = {Allowable Load / (Design Safety Factor * Limit Load)} - 1

NOTE Load may mean corresponding stress or strain.

3.22
minimum allowable
minimum material mechanical properties warranted by supplier

3.23
pressure
external load caused by fluid action on a structural surface

3.24
primary structure
part of the vehicle that carries the main loads and defines the fundamental resonance frequencies

3.25
rupture
loss of integrity by structure material differed from fatigue and ultimate creep deformation attainment, which can prevent the structure to withstand loads combinations

3.26
semi-finished item
product that is used for structure manufacturing or assembling

NOTE The typical examples are sheets, plates, profiles, strips etc.

3.27
stabilizing load
load, which if applied in conjunction with destabilizing loads, decreases comprehensive stresses

3.28
static strength
property of a structure, characterized by its possibility to withstand loads and temperatures combinations action without rupture, collapse, detrimental local buckling and detrimental deformation

3.29
strength failure mode
condition of a structure or structural member considered a critical condition in accordance with stress analysis results

3.30
stress analysis
analytical procedure to determine structure stress/strain distribution, deformations and margins of safety

3.31
structure
primary structure, unit attachments, pressure vessels, loads carrying elements of appendages

3.32
structure mathematical model
analytical or digital presentation of a structure

NOTE The model should provide adequate description of the structure's response under loads/pressures/temperatures.

3.33
ultimate load
limit load multiplied by ultimate design safety factor

3.34
unit
part of vehicle, which is designed mainly to provide vehicle functioning and differ from structure

4 Requirements

4.1 General

For structures used in space systems such as launch and space vehicles, the stress analysis and corresponding margin of safety determinations for various static strength failure modes shall meet the requirements specified in this International standard.

Basic data, structure models, methods for stresses analysis and strength criteria are considered as the integral parts of that procedure.

There are no limitations set out in this International standard, which restrict the application of results of stresses calculation for other purposes than those formulated below.

4.2 Basic data

Basic data used for the space structure stresses analysis shall meet the requirements of this clause. Basic data shall include all the following information:

— structure configuration, geometry and gages, and

— structure materials and their properties, and

— loading cases list, loads and temperatures combinations, and corresponding design safety factors for every loading case.

4.2.1 Structure configuration, geometry and gages

4.2.1.1 Structure configuration, geometry and gages data (with tolerance) used for stresses analysis shall be correspondent to drawings representing for design stage.

4.2.1.2 The choice of particular thickness (minimum or nominal) for stress analysis shall be based on national regulations requirements. Otherwise the following factors shall be taken into account:

— conservatism of applied safety factors and knockdown coefficients

— correspondence between applied thickness and procedure for knockdown coefficient determination

— stress analysis results dependence on and sensitivity to thickness

— simplification of stress analysis procedure application

— linear or non linear behavior.

4.2.1.3 Structure configuration, geometry and gages data (with tolerance) must be sufficient to substantiate structure analytical model and to determine corresponding parameters.

4.2.2 Structure materials and their properties

4.2.2.1 This entire chapter refers to individual material properties, as for any individual part of the structure (junctions, …) for which the stresses analysis requires allowable values.”

4.2.2.2 Materials list, which are used for structure and its members fabrication, shall be correspondent to design and technology documentation. The information about sorts of materials, semi-finished items and technology processes must be sufficient to evaluate possible variations of their properties used for stresses analysis and margins of safety determination.

4.2.2.3 Material properties used for stresses analysis and margins of safety determination shall take into account manufactory processes, temperature and other significant environmental effects including possible aging during lifetime.

If appropriate data are not available special development tests shall be conducted to evaluate corresponding properties.

4.2.2.4 Appropriate ultimate and yield strength (for metal only) material properties shall be used for margins of safety calculations. "A-basis allowable" values shall be used where failure of a single load path would result in loss of structural integrity. Redundant structural elements where failure of one element would result in a safe redistribution of applied loads to other elements, "B-basis allowable" values may be used. When it is difficult to obtain "A-basis allowable" and "B-basis allowable" it is permissible to use minimum values warranted by material supplier and approved by procuring agency.

Nominal modulus of elasticity and Poisson's ratio shall be used for the stress analysis.

4.2.2.5 If inertia loads are applied and corresponding basic data are described in the terms of accelerations or gravity constant, inertia material properties and masses of units and appendages data must be sufficient to determine those inertia loads adequately.

Nominal material inertia properties and nominal units and appendages masses and parameters of their arrangements shall be used for stress analysis. When an attachment can be used for different types of units or appendages, then nominal values for the most unfavorable type of equipment shall be taken into account.

NOTE When equipment inertia scattering is considered as significant one, the most unfavorable combinations of units and appendages masses and parameters of their arrangements shall be used for local stresses analysis in areas near corresponding attachments.

4.2.2.6 Temperature effects on material and physical properties and thermal stresses shall be considered.

NOTE When appropriate, it is permissible do not take into account thermal stresses for materials with high ultimate deformation (in comparison with thermal expansion) and low yield strength.

4.2.2.7 When loading out of elastic limit is permitted, and loads values are sufficient to cause a significant material nonlinear behavior exhibition, corresponding stress - stain dependencies shall be used for stresses analysis.

4.2.3 Loading data

Load data must include:

— list of loading cases;

— loads and temperatures combinations for every loading case;

Load data must include the ranges in which loads and temperatures can alter simultaneously for every loading case and every loading combination. Maximum loads values shall be limit loads.

In accordance with ISO STD 14622 the following types of external loads shall be taken into account, which can be generally classified as :

— mechanical loads (quasi static or equivalent quasi-static loads for stresses analysis)

— pressure loads (or equivalent quasi static pressure)

— thermal loads

— pretension loads.

4.3 Analysis methodology and software

4.3.1 Analysis methodology

4.3.1.1 Either closed form structural analysis techniques or numerical methods, such as finite element, boundary element methods, etc., may be used for stresses analysis and margins of safety determination separately or together (for example, stresses are calculated by using numerical method, and margins of safety corresponding to structural member local buckling are determined from an analytical result).

4.3.1.2 In case of numerical methods application the required accuracy shall be demonstrated.

4.3.1.3 Commonly used stress analysis methods shall be verified by comparison calculation results and known test data.

4.3.2 Software verification

4.3.2.1 Software used for stresses analysis must be verified by comparison results of calculation with theoretical results and (or) results obtained by using other verified software.

4.3.2.2 Verification procedure shall take into account typical structure models, boundary conditions, loading conditions, materials applied, convergence and stability of numerical methods used.

When knockdown coefficients are used as an input data for software application, verification must be conducted without their accounting for to provide the comparison with pure theoretical results.

4.4 Structure mathematical model

4.4.1 General

When applied for stresses analysis the structure mathematical model shall be generally developed by using appropriate experience based on the results of flight-type hardware tests.

If such experience is not available or considered as not applicable to a particular case, special development tests shall be conducted for structure model validation.

The structure mathematical model shall be developed to take into account the structure configuration, materials applied, loading, environmental conditions and type of analysis.

Structure mathematical model shall be checked for correlation with available test data.

4.4.2 Boundary conditions

Boundary conditions are an integral part of the structure analytical model. The adjacent structures influence on loads transmission, stresses distribution and collapse mode shall be evaluated to provide adequate loading conditions of the structure under consideration. When any applied boundary conditions do not represent the actual stress distribution, adjacent structure or sufficient large part of adjacent structure analytical model shall be developed and incorporated into the model of the structure under consideration.

Notwithstanding that requirement, simplification of boundary conditions is permitted, such as reducing to conservative conditions or to effective stiffness, however it shall be demonstrated that those simplifications provide conservative result.

In general the adjacent structure model development requirements are the same as for the structure under consideration except only stiffness and loads transmission should be modeled properly.

4.5 Structure mathematical model check

When computerized numerical methods are used for stress analysis, the structure mathematical model checks in Annex B should be conducted in maximum possible extent in frames of used software possibilities.

4.6 Failure modes

4.6.1 General

The strength criteria application shall be based on the appropriate experience including flight-type hardware testing with accounting for basic data, structure model, knockdown coefficients and fabrication technology. When appropriate experience is not available or in case of doubt, special development tests shall be conducted for criteria validation.

4.6.2 Detrimental yielding

Margin of safety for detrimental yielding failure mode shall be determined for prescribed loads combinations presented in loading data. It is considered that detrimental yielding failure mode is realized when stress (strain) levels in prescribed locations are equal to or higher than corresponding yield material properties.

4.6.3 Rupture

Margins of safety for rupture failure mode shall be determined for any loads combination presented in loading data.

It is considered that rupture failure mode is realized when stress (strains) levels in any location of the structure are equal to or more than corresponding ultimate material properties.

4.6.4 Collapse

Margins of safety shall be determined for collapse failure mode if comprehensive stresses can occur, when loads alter in specified ranges.

Criterion for this failure mode is the indication of proper buckling analysis that collapse is realized for given loads combination. For collapse analyses the initial deformations due to manufacturing and thermal deformations due to temperature gradients shall be taken into account. It is permissible to take them into account by applying of corresponding knockdown coefficients.

4.6.5 Local buckling

Margins of safety for local buckling of all structural parts shall be determined if compressive stresses can occur in these parts, when loads alter in specified ranges. If the margin of safety is smaller than zero for a part (parts) of the structure and local buckling is not considered as failure mode and it is acceptable at system level, margins of safety for other failure modes shall be determined with accounting for buckled elements.

Criterion for this failure mode is the indication of proper buckling analysis, that local buckling is realized for given stresses combination. For local buckling analyses the initial deformations due to manufacturing shall be taken into account. It is permissible to take them into account by applying of corresponding knockdown coefficients.

4.7 Critical location analysis

Loading conditions and stresses distribution analysis shall be carried out to define critical locations where material or structural members are most sensitive to a failure mode attainment.

The most unfavorable combinations of loads and temperatures in frames of specified ranges shall be accounted when margins of safety are determined for every critical location.

4.8 Margins of safety determination

4.8.1 Margins of safety (MS) shall be calculated by the formula (1):

$$MS = \left[\frac{AL}{(f \times LL)} \right] - 1 \qquad (1)$$

where:

AL = allowable load under specified functional conditions (e.g. yield, rupture, collapse, local buckling), which shall be determined in accordance with criteria stated in the clause 4.6 and requirements of the clause 4.2.

LL = limit load

F = design safety factor.

In Annex A an example of application is presented for the case of several loads combination.

The application of design safety factors is the integral account of many different issues such as loads statistical distributions, accuracy of loads and stress analysis models, manufactory technology level, possibility of test methods and facilities to provide adequate loading conditions, etc.

NOTE Margins of safety express the margin of the design load (f*LL) against the allowed load. Loads can be replaced by stresses if the load-stress relationship is linear. In the case of significant influence of residual stress this stress shall be taken into account when margin of safety is determined.

4.8.2 For collapse and local buckling failure modes stabilizing loads shall be accounted in conjunction with design safety factor 1.0. If otherwise specified, minimum values of stabilizing loads (in the prescribed ranges) shall be used instead of maximum ones in this case.

4.8.3 Margins of safety, calculated in accordance with equation (1), shall be non-negative for every loading case and loading combination specified in basic data to demonstrate that structure meet strength requirements.

4.8.4 As an alternative approach reserve factor (η) may be determined by the equation (2).

$$\eta = \frac{AL}{(f \times LL)} = MS + 1 \qquad (2)$$

The requirement $\eta \geq 1.0$ is mathematically equivalent to the requirement formulated in the clause 4.8.3.

4.9 Report

As a result of the stress analysis activity a stress analysis report shall be issued. The report shall consist of :

- Basic data, including:
  - Structure configuration, geometry and gages
  - Structure materials and their properties
  - Limit loads/pressures/temperatures for every loading case considered
  - Safety factors for every loading case and structure elements considered
- Structure mathematical model description, including:

  - Rationales for its choice
  - Boundary conditions
- Structure mathematical model checks and their results
- Failure modes considered
- Strength criteria applied
- Description or references to methods and software applied
- Summary of significant analysis results including the information on structural element considered, loading case, failure mode, safety factor corresponding to failure mode, margin of safety (or reserve factor).

It shall be clearly indicated in the Report the additional margins, if any applied.

The analysis shall be revised and updated whenever changes of basic data could occur, stress analysis report shall be revised to take into account corresponding results.

Annex A
(informative)

Margin of safety determination example for the case of several loads combination

A.1 When loads combination is applied to a structure, it is assumed that all loads alter from zero simultaneously and proportional to some parameter λ. When this parameter equals 1.0, it is correspondent to design loads combination. In the case of collapse and local buckling stabilize loads should be accepted not altered and equaled to prescribed values. Margin of safety is determined by the equation (A.1):

$$MS = (\lambda) - 1 \qquad \text{(A.1)}$$

where:

[λ] – value of the parameter λ, corresponding allowable loads combination (loads combination when critical condition is realized)

An alternative approach can be applied for the case of several loads combination. The method of interaction equation leads to solve an equation of this type:

$$\lambda^{\alpha} R_1^{\alpha} + \lambda^{\beta} R_2^{\beta} + \lambda^{\chi} R_3^{\chi} \ldots = 1 \qquad \text{(A.2)}$$

where the ratios R between applied and allowable loads, and the exponents of α, β, γ … (rational numbers) are known. By solving analytically or numerically this equation, the minimum λ can be found and then the margin of safety (λ-1) can be computed.

In the case of doubts that ultimate loads combination could not be the most unfavorable one (e.g., when structure exhibits significant nonlinear behavior and/or essentially nonlinear strength criteria are applied) the MS sensitivity should be investigated to ultimate loads values variations inside prescribed ranges and minimum MS is determined.

A.2 When the combination of loads application can be substituted by an application of one load, which is a function of other loads and is considered as equivalent one, this load can be used in the equation (1) for margin of safety determination. Typical example is an equivalent axial load (NE) for the case of axial load (N) and bending moment (M) application to cylindrical shell of diameter D:

$$N_E = N + 4\left(\frac{M}{D}\right) \text{ (tension)} \qquad \text{(A.3)}$$

$$N_E = N - 4\left(\frac{M}{D}\right) \text{ (compression)}$$

A.3 When the combination of loads application can be described at the critical location by some equivalent specific load (flux), which is a function of loads, this flux can be used in the equation (1) for margin of safety determination. Typical example is the case of axial load (N) and internal pressure (P) application to cylindrical shell of diameter D:

$$flux = \frac{N}{\pi D} + \left(\frac{P \times D}{4}\right) \text{ (for axial stresses)} \qquad \text{(A.4)}$$

Annex B
(informative)

Structure mathematical model check

B.1 General

When computerized numerical methods are used for stress analysis, the following structure mathematical model checks should be conducted in maximum possible extent in frames of used software possibilities.

B.2 Mass check

It should be checked that the total mass of the mathematical model is not differ from mass indicated in approved system documentation more than of 1.0%

B.3 Center of gravity check

It should be checked that the center of gravity of the mathematical model are not differ from center of gravity indicated in approved system documentation more than of 1.0% of maximum structure analyzed dimension

B.4 Inertia check

It should be checked that inertia tensor elements values of the mathematical model are not differ from values indicated in approved system documentation more than of 1.0% of maximum inertia tensor elements value

B.5 Free-free check

To conduct this check lower frequencies of the mathematical model are determined. It should be checked that at least 6 frequencies are presented with absolute values not higher then 0.005 Hz. If more then 6 quasi-zero frequencies are presented, than it should be explained by specific structure configuration

B.6 Strain energy check

To conduct this check, rigid body modes corresponding to quasi-zero frequencies (see p. "B.5" above) are determined for the mathematical model with free-free boundary conditions. Modes are normalize so that displacements are equal 1 meter and rotations are equal 1 radian. Strain energy matrix is defined as

$$E = 0{,}5\Phi^T K\Phi ,$$

where Φ is the matrix with rigid body modes as columns and K is the stiffness matrix of the mathematical model.

It should be checked that diagonal elements of matrix E are not higher than 10^{-3} N*m

B.7 Gravity load check

Gravity load of 1 “g” value is applied consequently along each axis of the used Cartesian coordinate system for the mathematical model with boundary conditions, correspondent to required stress analysis. It should be checked that total reaction for corresponding direction is equal to the mathematical model weight. It should be also checked that at any boundary point desirable reactions are presented in desirable directions.

B.8 Thermal check

This check is conducted for the mathematical model with free-free boundary conditions and in the absence of rigid links between nodes, which prevent any relative deformation of these nodes. Uniform temperature field $\Delta T=100$ K is applied to the mathematical model. The Poison’s ratio of 0.3 and thermal expansion coefficient of $\alpha=10^{-5}$ are used for this check. It should be checked that resulting stress is negligible at any structure location

B.9 Artificial stiffening check

If artificial stiffening is used in the mathematical model for the specific purposes, it should be checked that it does not cause unrealistic vibration modes arising.

B.10 The node ratio check

To conduct this check maximum and minimum diagonal elements of stiffness matrix are determined for each node of the mathematical model. It should be checked that the ratio of minimum value to maximum one is higher than 10^8 for any node.

B.11 Maximum ratio check

To conduct this check the mathematical model stiffness matrix with boundary conditions is normalized as

$$K = LDL^T ,$$

where L is triangle matrix and D is diagonal matrix.

The ratio (K diagonal element)/(corresponding D diagonal element) is determined for each row of stiffness matrix. It should be checked that the ratio is lower than 10^7 for any row of stiffness matrix